

# Analysis of Stars Common to the IRAS and HIPPARCOS Surveys

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## ABSTRACT

For about 11,000 stars observed in the HIPPARCOS Survey and detected by IRAS we calculate bolometric luminosities by integrating their spectral energy distributions from the B band to far-IR wavelengths. We present an analysis of the dependence of dust emission on spectral type and correlations between the luminosity and dust emission for about 1000 sources with the best data (parallax error less than 30%, error in luminosity of  $\sim 50\%$  or better). This subsample includes stars of all spectral types and is dominated by K and M giants.

We use the IRAS [25]-[12] color to select stars with emission from circumstellar dust and show that they are found throughout the Hertzsprung-Russell diagram, including on the main sequence. Clear evidence is found that M giants with dust emission have luminosities about 3 times larger ( $\sim 3000 L_{\odot}$ ) than their counterparts without dust, and that mass loss on the asymptotic giant branch for both M and C stars requires a minimum luminosity of order  $2000 L_{\odot}$ . Above this threshold the mass-loss rate seems to be independent of, or only weakly dependent on, luminosity. We also show that the mass-loss rate for these stars is larger than the core mass growth rate, indicating that their evolution is dominated by mass loss.

*Subject headings:* circumstellar matter: dust — infrared: stars — stars: AGB and post-AGB, fundamental parameters, mass-loss — surveys

## 1. Introduction

Dust can be found around pre-main-sequence, main sequence, and post-main-sequence stars (e.g. Zuckerman 1980, Habing 1996, Waters & Waelkens 1998). The relationships

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between the luminosity of a star, its evolutionary phase, and the properties of its circumstellar dust are not fully understood. The main obstacle is the lack of a large uniform sample which would include both dust emission properties and the stellar luminosity and spectral type. In this paper we present such a sample of stars for which these quantities are obtained by combining the results of the IRAS and HIPPARCOS surveys. While there have been studies correlating IRAS data with data from other catalogs (e.g. with the SAO catalog, Oudmaijer *et al.* 1992), the determination of luminosity for a large number of stars has become possible only recently due to the release of the HIPPARCOS astrometric data.

The Infrared Astronomical Satellite (IRAS) produced a 96% of the sky survey at 12, 25, 60 and 100  $\mu\text{m}$ , with the resulting IRAS point source catalog (IRAS PSC) containing over 250,000 sources. The colors based on IRAS fluxes can efficiently be used to distinguish pre-main sequence from post-main sequence stars, and to study characteristics of the dust emission (e.g. van der Veen & Habing 1987, Ivezić & Elitzur 2000, hereafter IE00). The recently released HIPPARCOS (High Precision PARallax Collecting Satellite) catalog contains parallaxes of unprecedented accuracy for 118,218 sources, and is complete to  $V \sim 7.5$  (Perryman *et al.* 1997). Combining these two data sets can yield bolometric luminosities for a large number of stars, and facilitate studies of the relationship between the characteristics of dust emission and stellar luminosity.

In Section 2 we describe a catalog of stars obtained by positionally matching the IRAS and HIPPARCOS catalogs. For 11,321 matched sources we calculate bolometric fluxes by integrating their spectral energy distributions (SED) from the B band to far-IR wavelengths, and with the aid of HIPPARCOS parallaxes, bolometric luminosities. In Section 3, we present an analysis of the dependence of dust emission on spectral type and correlations between the luminosity and dust emission for 968 sources with the most accurate luminosities (standard deviation of  $\sim 50\%$  or better), and in Section 4 we discuss the relationship between mass loss and luminosity for asymptotic giant branch (AGB) stars.

## 2. The Synthesis of the IRAS PSC and HIPPARCOS Catalogs

We consider only sources from the IRAS PSC with quality flags of at least 2 in at least 2 IRAS bands<sup>3</sup>. This is motivated by the results described in IE00 who showed that dusty stars come in two “flavors”: AGB stars which typically have fluxes in the 12 and 25  $\mu\text{m}$  bands larger than the fluxes in the 60 and 100  $\mu\text{m}$  bands, and various young stellar objects with fluxes in the 60 and 100  $\mu\text{m}$  bands larger than the fluxes in the 12 and 25  $\mu\text{m}$  bands.

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<sup>3</sup>The reliability of an IRAS flux is described by the quality index: 3 – high, 2 – low, 1 – an upper limit.

There are 88,619 sources with high-quality fluxes in the 12 and 25  $\mu\text{m}$  bands, and 33,435 sources with high quality fluxes in the 60 and 100  $\mu\text{m}$  bands. We note that the number of sources with good fluxes at only 25 and 60  $\mu\text{m}$  is very small compared to the above (3612, or less than 3%), in agreement with IE00.

The quoted IRAS positional  $2\sigma$  error ellipse for stars is typically  $3'' \times 20''$ , and its position angle varies across the sky (Beichman *et al.* 1988). However, the typical distance between HIPPARCOS sources (about  $30'$ ) is much larger than the IRAS error ellipse, and we simply match the positions of stars within a circle of radius  $25''$ . This matching radius ensures that practically all true matches are included, while keeping the random association rate below  $\sim 5 \times 10^{-4}$ . Also, this radius is sufficiently small that the number of Hipparcos sources matched with multiple IRAS sources is negligible (there are only 4 such cases for which we took the closer match). The positional correlation of the subset of  $\sim 125,666$  IRAS sources with the full HIPPARCOS catalog resulted in 11,321 matches. The positional discrepancies are consistent with the mean IRAS error of  $\sim 10''$ . From the random association rate we estimate that about 50 matched sources (0.4% of the sample) are random associations<sup>4</sup>. We estimate the completeness of our matched sample by increasing the matching radius to  $45''$  which produces 11,853 matches. Taking into account the increase in the expected number of random associations, this implies that our adopted sample includes  $\sim 95\%$  of all true HIPPARCOS–IRAS associations.

As expected, the matched sources are predominantly red HIPPARCOS stars, and the majority satisfy  $0.9 < B - V < 1.6$  and  $V < 9$ . When considering the IRAS catalog, 77% of sources matched in the HIPPARCOS catalog are dust-free stars (see Section 3) brighter than 1 Jy at 12  $\mu\text{m}$ . The faint limit for the matched dust-free stars with “blue” SEDs is imposed by the IRAS sensitivity. The faint cutoff for matched dusty stars (approximately 2 times brighter than the cutoff for the input IRAS sample) with “red” SEDs is imposed by the HIPPARCOS sensitivity. Because of this cutoff, the matching of the HIPPARCOS catalog to a deeper IR catalog, e.g. IRAS Faint Source Catalog, would not significantly increase the sample of dusty stars with good distance estimate.

For all matched stars we calculate bolometric fluxes by integrating their SEDs from the B band to the IRAS 100  $\mu\text{m}$  band. We use photometric measurements provided by the HIPPARCOS main catalog and from the Catalog of Infrared Observations, which consists of inputs from other catalogs and observations culled from the literature, beginning in 1965 (CIO, Gezari *et al.* 1993). The number of flux measurements per star ranges from 6 to

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<sup>4</sup>This number could be decreased by about factor 2 by explicitly treating the IRAS error ellipse information, but this doesn’t seem necessary since the contamination is already negligible.

$\sim 20$  with a median value of 10. We have used 2 integration methods: linear interpolation in  $\log(\lambda) - \log(\text{flux})$  space and piecewise fitting of the Planck curve. The two methods typically agree within 20 - 30%. From the piecewise fitting of the Planck curve to the end point pairs we estimate the flux outside the observed wavelength range to be typically less than 10%. From the bolometric fluxes and HIPPARCOS parallaxes we calculate bolometric luminosities for all 11,321 stars.<sup>5</sup>

Figure 1 displays the luminosity histogram for a subsample of matched stars with maximum fractional error in parallax of 30% and at least 9 fluxes used for the bolometric flux calculation (968 stars). Relaxing the parallax cutoff to 50% roughly doubles the sample size but noticeably increases the number of outliers in various diagrams to be discussed later. The top panel in Figure 1 shows the distribution for all stars, irrespective of spectral type<sup>6</sup>. The error bars are assigned assuming a Poisson error distribution. There are two obvious peaks at  $\sim 50 L_{\odot}$  and  $\sim 1000 L_{\odot}$ . The six panels below detail the same information separated by spectral type; all luminosity classes are included. Since there are so few O and B stars in the sample they are treated together. The numbers of stars in each spectral type subsample, given below the spectral type designation in each panel, show that the sample is dominated by K and M giants. The comparison of the histogram for the full sample, displayed in the top panel, to the various spectral subsamples, shows that the peak at  $\sim 50 L_{\odot}$  is due to K sub-giants, also known as the red clump stars (for a detailed discussion see Oudmaijer *et al.* 1992), and that the peak at  $\sim 1000 L_{\odot}$  is due to M giants (note that the HIPPARCOS magnitude limit detects M dwarfs only out to 5 pc).

From the width of the peak for K stars at  $\sim 50 L_{\odot}$  we estimate an upper limit on the mean  $L_{\text{bol}}$  error of  $\sim 50\%$  (were this error larger, this peak could not be so narrow). Assuming that HIPPARCOS parallaxes and our method for determining bolometric fluxes are not biased with respect to spectral type, we adopt this value as the mean  $L_{\text{bol}}$  error for the whole sample. However, we note that dusty stars with heavily reddened SEDs may have large errors due to sparse infrared photometry, and the error distribution in such a case would be markedly non-Gaussian.

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<sup>5</sup>We ignore the correction for interstellar extinction since the sample is dominated by nearby stars ( $\lesssim 300$  pc).

<sup>6</sup>The histogram counts are expressed as normalized counts per unit log interval ( $\text{dex}^{-1}$ ); that is, the integrals of the plotted curves over  $d(\log L_{\text{bol}})$  are unity.

### 3. The Relationship between Luminosity and Spectral Properties

Figure 2 shows  $L_{\text{bol}}$  vs.  $[25]\text{--}[12]$  color<sup>7</sup> for 913 stars from Figure 1 with IRAS flux qualities of at least 2 at 12 and 25  $\mu\text{m}$ , and with known spectral types. Color temperature increases from right to left, and  $[25]\text{--}[12] = -0.6$  corresponds to the Rayleigh-Jeans tail of the Planck function. Stars with this color have no dust, and the distribution width indicates the errors in the IRAS fluxes ( $\lesssim 10\%$ ). Stars with  $[25]\text{--}[12] \gtrsim -0.5$  emit more infrared radiation than a pure black-body; this excess is usually attributed to dust emission (however, the infrared excess for some O and B stars may be dominated by free-free emission). A significant fraction ( $\sim 60\%$ ) of B and A stars show such infrared excess and are probably young pre-main sequence stars (Herbig Ae/Be stars, Waters & Waelkens 1998). A few F and G stars with infrared excess are probably post-asymptotic giant branch stars (Oudmaijer *et al.* 1992). The M stars are shown in the lower-right panel, and are further discussed in §4. However, it can already be seen in this diagram that M stars with dust are typically more luminous than those without dust. Note also that early-type stars (OBA) with infrared excess have much redder  $[25]\text{--}[12]$  colors (up to  $\sim 1$ ), than M stars with infrared excess ( $\lesssim 0$ ). This difference is due to different dust density distributions in the circumstellar envelopes which are flatter for early-type stars than for late-type stars (IE00).

Fig. 2 shows that stars with mid-infrared excess can be simply selected as those with  $[25]\text{--}[12] > -0.5$ . Figure 3 displays  $L_{\text{bol}}$  vs. B-V diagrams for a subsample of 947 stars satisfying  $V < 11^{\text{m}}$ , with (239) and without (708) infrared excess, marked by triangles and crosses, respectively. It is easily discernible that dusty stars are found throughout the HR diagram. The three dominant dusty populations are early type OBA stars with  $L_{\text{bol}} \gtrsim 10 L_{\odot}$  and  $B\text{--}V \lesssim 0.6$ , and two types of late-type stars (further discussed in the following Section) with  $L_{\text{bol}} \sim 10^3\text{--}10^4 L_{\odot}$ : M stars with  $B\text{--}V \sim 1.3$  and carbon stars with  $B\text{--}V \gtrsim 2.0$  (Wallerstein & Knapp 1998).

### 4. Dust around AGB Stars

Asymptotic Giant Branch (AGB) stars are intermediate mass stars in a late evolutionary stage just preceding the planetary nebula phase. Due to copious mass loss (up to several  $10^{-4} M_{\odot}/\text{yr}$ ), they are surrounded by dusty shells which emit distinctive infrared radiation (for an extensive review see Habing 1996). It is not clear what the relationship is between the

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<sup>7</sup>We define IRAS  $[25]\text{--}[12]$  color as  $\log(F_{25}/F_{12})$ , where  $F_{12}$  and  $F_{25}$  are the flux densities taken from the IRAS PSC catalog.

mass-loss rate and luminosity for AGB stars. Early studies by Gilman (1972) and Salpeter (1974), and later by others (e.g. Netzer & Elitzur, 1993; Habing, Tignon, & Tielens, 1994), showed that the luminosity-to-mass ratios for AGB stars are sufficiently large that mass loss could be driven by radiation pressure. Furthermore, Ivezić & Elitzur (1995, hereafter IE95) find that steady-state, radiation pressure driven outflow models can explain IRAS colors for at least 95% AGB stars. However, in these models both the mass-loss rate and the stellar luminosity are free parameters, and cannot be independently constrained from the observations. We use the available luminosity and infrared colors for the sample of M giants discussed here to study this relationship.

The top panel in Figure 4 shows the bolometric luminosity vs. [25]-[12] color diagram for a subsample of 307 M stars with distances less than 300 pc. The luminosities of 255 stars without dust emission ( $[25]-[12] < -0.5$ ) cluster around  $L_{\text{bol}} \sim 1000 L_{\odot}$ , while 52 stars with dust emission have luminosities on average  $\sim 3$  times larger. Only 5% of stars without dust emission have  $L_{\text{bol}} > 3000 L_{\odot}$ , and only 13% of stars with dust emission have  $L_{\text{bol}} < 1000 L_{\odot}$ . This difference in bolometric luminosity distributions is better seen in histograms shown in the bottom pane, which are plotted separately for each subsample. Figure 4 indicates that there is a characteristic luminosity of order  $2000 L_{\odot}$  for stars to develop a dusty envelope. Above this value the luminosity does not seem to be correlated with [25]-[12] color and its median luminosity for dusty M stars is  $\sim 3000 L_{\odot}$ .

The scatter of points for dusty M stars around the median luminosity is somewhat larger than the expected errors derived in §3, and thus may be real. However, the procedure used to determine bolometric flux is expected to be less accurate for stars emitting mostly in the infrared due to sparse flux sampling. The method employed here for estimating bolometric flux can be significantly improved by utilizing detailed radiative transfer models for stars embedded in dusty envelopes. When fitting a model to the observed fluxes, the model SED acts as a smooth interpolating function which produces a more robust estimate of the bolometric flux than an arbitrary function such as a piecewise power-law (the bolometric flux is simply a scaling parameter, see Ivezić & Elitzur 1997). Such a detailed model fitting of a large number of sources will be presented in a separate publication.

The difference in median luminosities of stars with and without dust emission could be due to biased selection procedure. For example, if somehow dusty stars with  $L_{\text{bol}} \lesssim 1000 L_{\odot}$  are excluded from the sample, then the median luminosity of the remaining subsample is overestimated. We have tested our sample for this and similar possibilities by relaxing the constraints on parallax, parallax error, V and  $F_{12}$ , both individually and in various combinations. We find that the difference in median luminosity between the two subsamples is a robust result, even when the relaxed selection cuts result in a three times larger sample.

Of course, in this case the scatter in luminosity around the median values is also increased, and we find that such outliers are mostly stars with relatively large parallax errors. Most notably, changing the distance cutoff from 200 pc to 500 pc does not effect the median luminosities of the two subsamples.

The median luminosity for dusty M stars obtained here ( $3000 L_{\odot}$ ) is remarkably similar to the luminosity of AGB stars detected towards the Galactic bulge ( $\sim 2600 L_{\odot}$ ), as determined by Habing *et al.* (1985). This strongly suggests that the luminosity of AGB stars is roughly the same throughout the Galaxy, and is also the same for stars with different mass-loss rates (the stars discussed by Habing *et al.* are significantly redder at IRAS wavelengths than the stars discussed here which were selected from optical catalogs). It is of interest to find out whether this conclusion also holds for AGB stars with carbonaceous dust grains. Due to different optical properties of silicate and carbonaceous grains, these stars do not show a large increase of [25]-[12] color for plausible mass-loss rates (IE95), and thus their mass-loss rate cannot be inferred from their [25]-[12] color. Nevertheless, the mass-loss rate for C stars can be determined from the intensity of their CO emission and we utilize such observations to study the relationship between the mass-loss rate and bolometric luminosity for AGB stars with carbonaceous dust grains.

Figure 5 shows the mass-loss rate versus bolometric luminosity for a sample of 60 C stars with available CO emission observations (Knapp 2000). Distances are from the HIPPARCOS catalog for stars marked as filled circles, and indirectly determined (Knapp 2000) for stars marked by open circles. The mass-loss rate for stars not detected in CO, marked by triangles, is determined from their IRAS  $60 \mu\text{m}$  fluxes as described in Jura (1991). The distribution of sources shows that for C stars there seems to be a threshold luminosity of the order  $2000 L_{\odot}$  for stars to develop a dusty envelope. Similarly to the result found for M stars, above this threshold the luminosity does not seem to be correlated with mass-loss rate. This threshold luminosity of about  $2000 L_{\odot}$  is in agreement with the theoretical estimate expected for radiatively driven winds (e.g. Ivezić, Knapp & Elitzur 1998, and references therein).

Figure 5 also shows a line corresponding to

$$\dot{M}_{core} = \frac{L_{bol}}{0.007c^2},$$

the approximate rate at which the inert helium core is growing from hydrogen shell burning (Schönberner 1983). At all luminosities the mass-loss rate is larger than the core mass growth rate, indicating that mass loss dominates the evolution of these stars, in agreement with Wallerstein & Knapp (1998). Assuming the [25]-[12] color to mass-loss rate transformation as given by IE95, we find that the same conclusion also holds for M stars (c.f. Figure 4).

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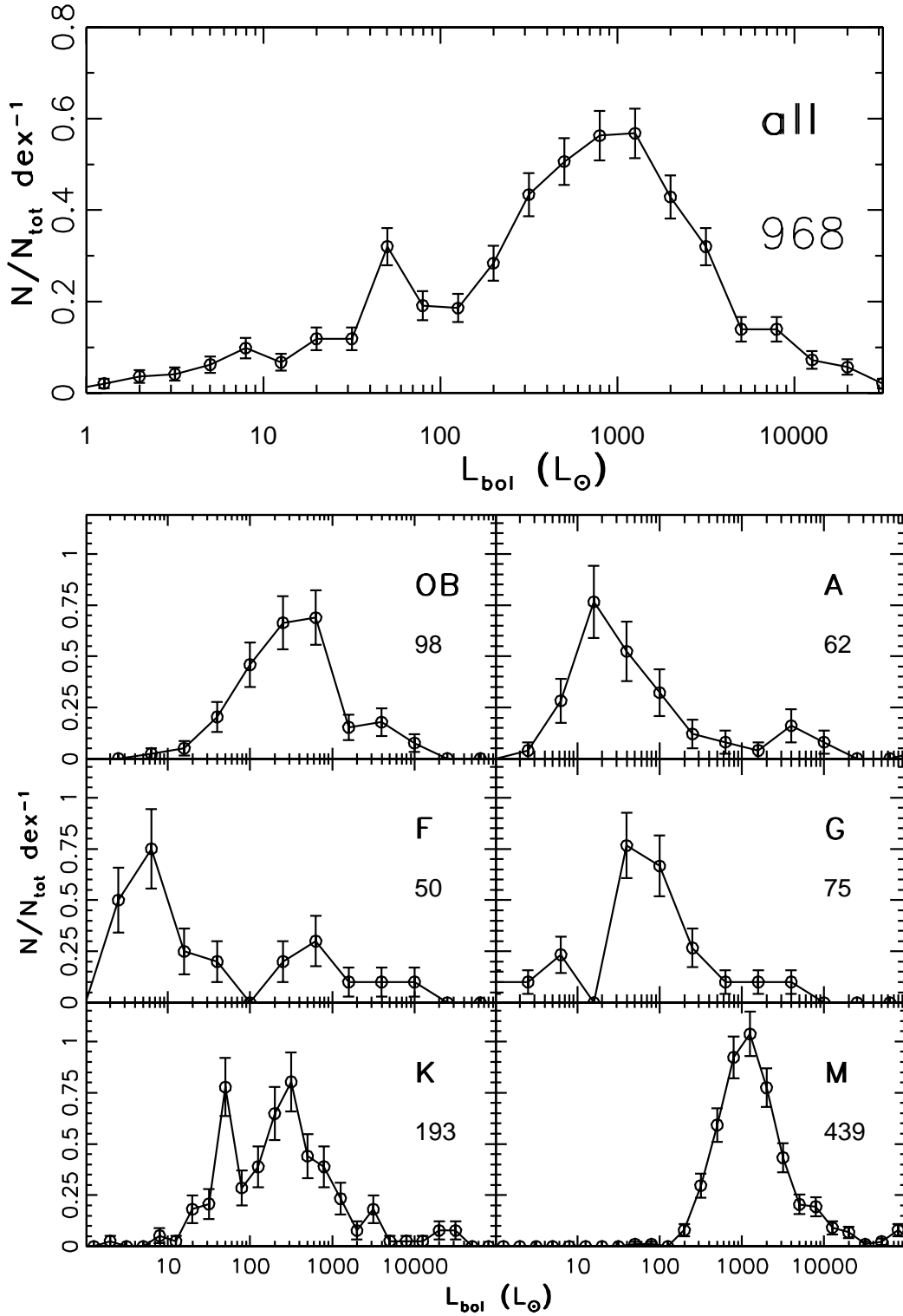


Fig. 1.— Luminosity histogram for 968 stars with most reliable luminosity estimates (see text). The top panel shows the distribution for all stars irrespective of spectral type, and the six panels below detail the same information separated by spectral type; all luminosity classes are included. The number of stars in each spectral type subsample is given below the spectral type designation in each panel.

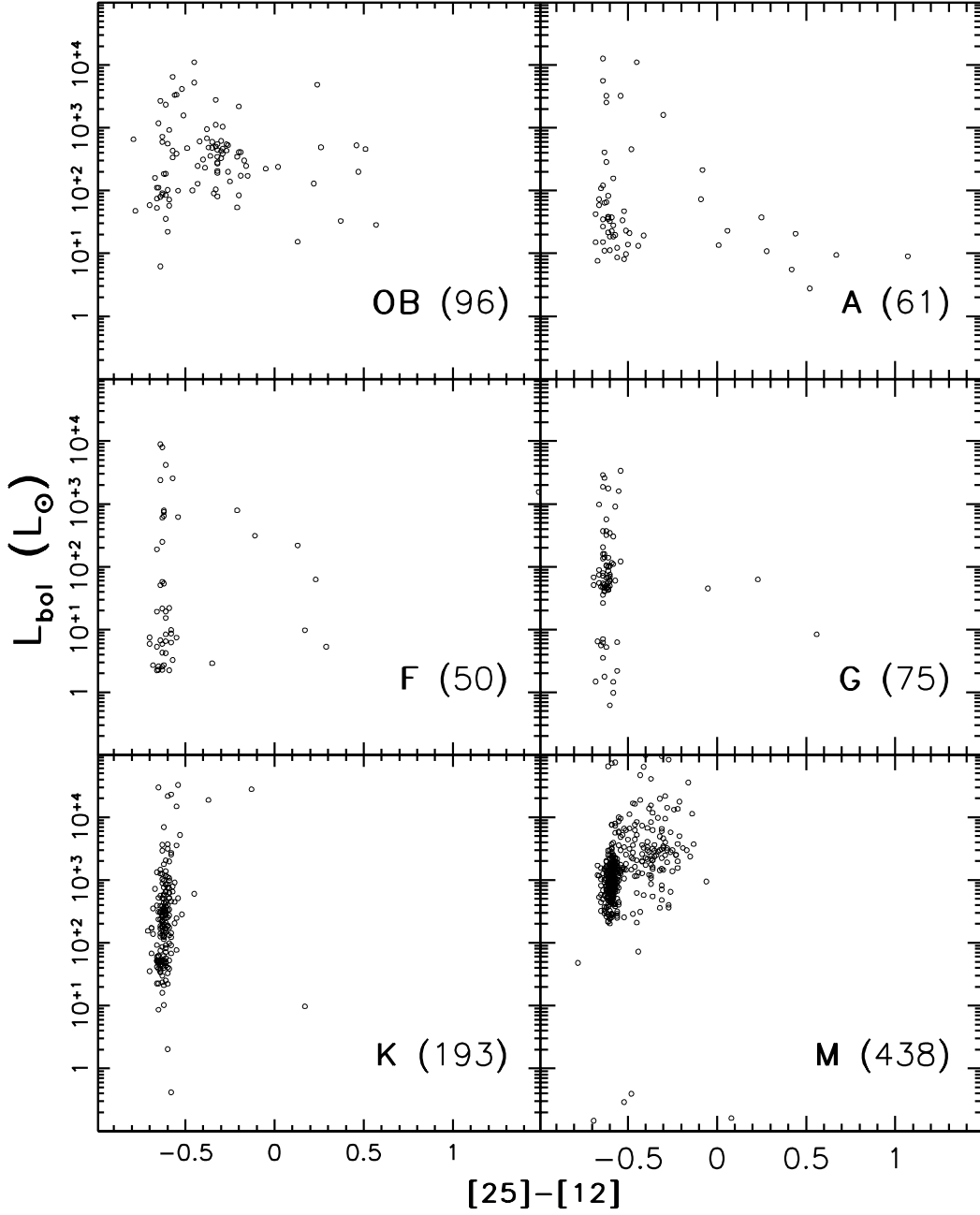


Fig. 2.— Bolometric luminosity –  $[25]-[12]$  diagram for 913 stars, marked by dots, from Figure 1 which have IRAS flux qualities at 12 and 25  $\mu\text{m}$  of at least 2, and have known spectral types. Panels show different spectral types, as marked.

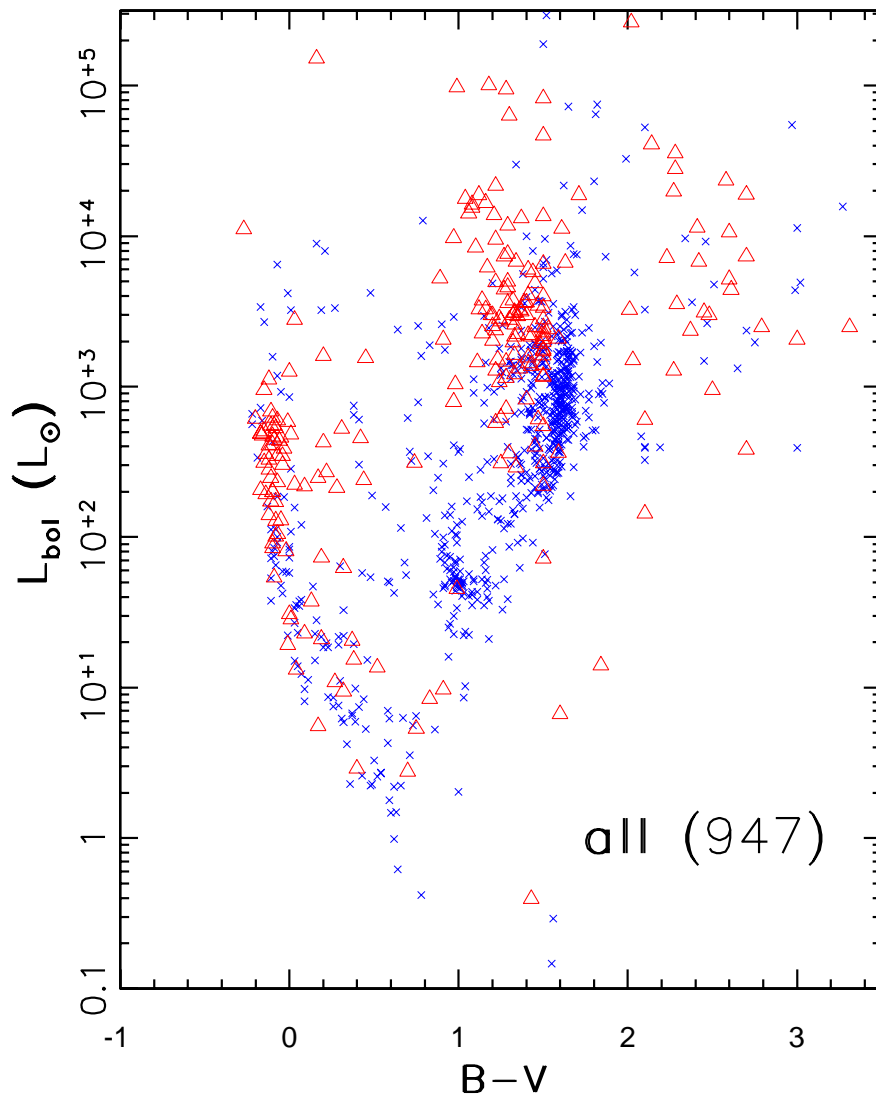


Fig. 3.— Bolometric luminosity –  $B-V$  diagram for 947 stars from Figure 1 with  $V < 11^{\text{m}}$ .  
 Triangles:  $[25]-[12] > -0.5$ . Crosses:  $[25]-[12] < -0.5$

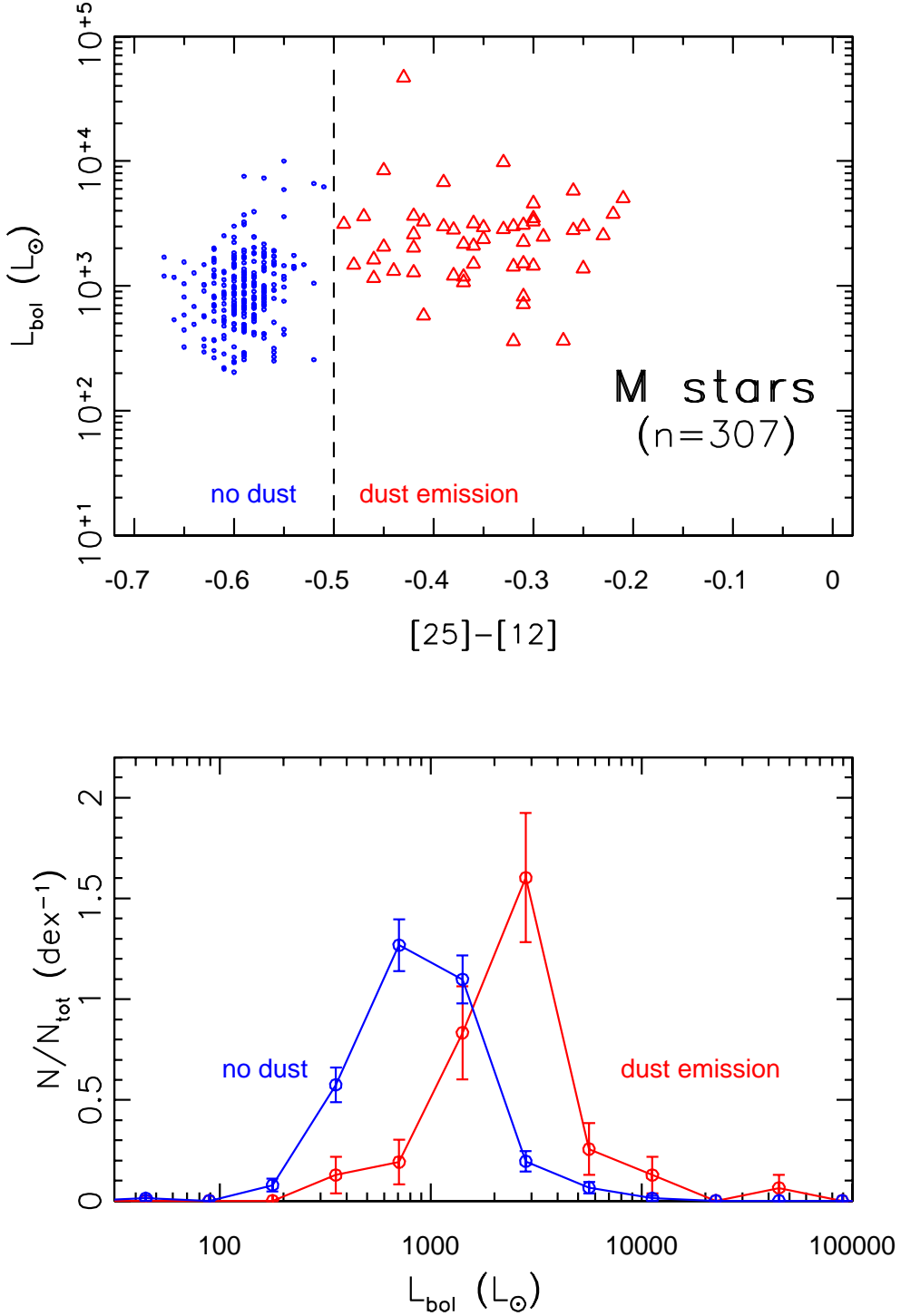


Fig. 4.— Top panel: bolometric luminosity –  $[25]-[12]$  diagram for 307 M giants with distances less than 300 pc. Bottom panel: luminosity histogram for non-dusty vs. dusty M giants, as implied by their  $[25]-[12]$  color.

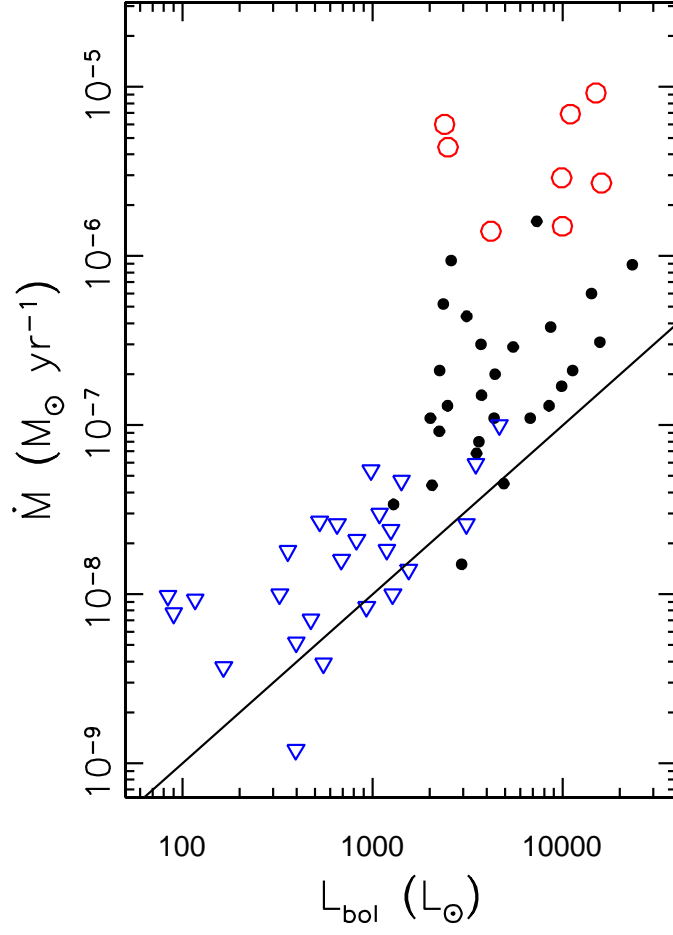


Fig. 5.— Mass-loss rate vs. bolometric luminosity for C stars (various symbols correspond to different methods for estimating mass-loss rate and distance, see text). The line indicates the core mass growth rate.